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Petrashov et al.

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(54) **QUANTUM INTERFERENCE DEVICE, DEVICE INCORPORATING SAME, AND METHOD OF MANUFACTURING A QUANTUM INTERFERENCE DEVICE**

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(73) Assignee: **Royal Holloway and Bedford New College**, Egham (GB)

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This patent is subject to a terminal disclaimer.

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CPC ***G01R 33/0354*** (2013.01); ***G01R 33/035*** (2013.01)

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CPC H01B 13/00; H01B 13/106; H01B 12/00; H01B 1/00; G01R 33/3802;
(Continued)

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(57) **ABSTRACT**

A quantum interference device includes a superconducting loop interrupted by a normal conductor segment, and an interferometer connected to the normal conductor segment, wherein the superconducting loop includes a plurality of turns. The turns can be a plurality of adjacent lobes. A coil can be located within a lobe of the superconducting loop. Optionally, a bridge layer (e.g., of gold) is formed above the substrate to make an electrical contact between a superconducting layer (e.g., of niobium) formed above the bridge layer and a normal conducting layer (e.g., of titanium) formed above the bridge layer. The bridge layer allows the device to be formed of superconducting and normal con-
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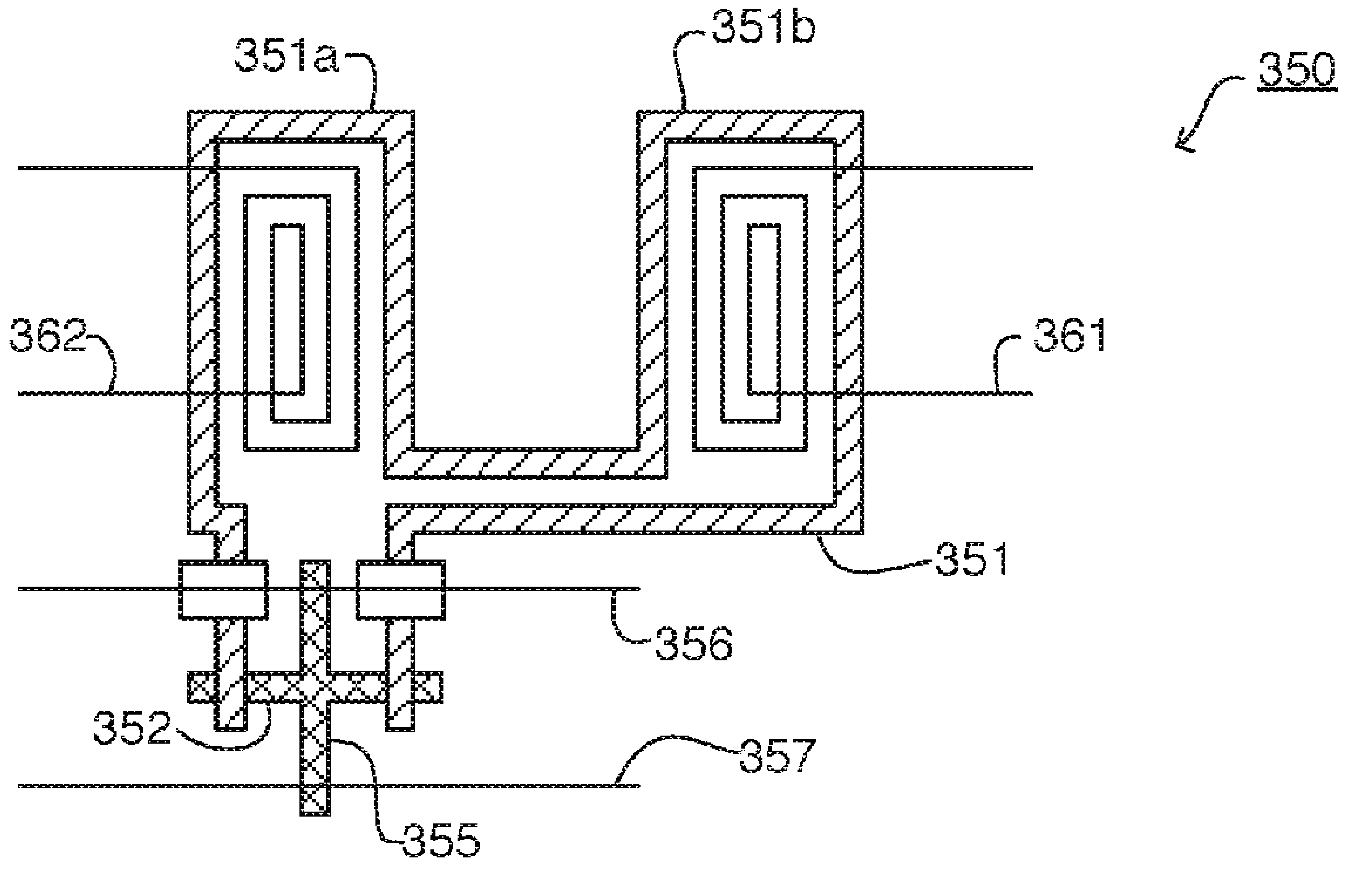

ducting material that are otherwise incompatible. A titanium normal conducting layer can be allowed to oxidize over a period of years.

9 Claims, 6 Drawing Sheets

(58) **Field of Classification Search**
CPC G01R 33/3815; G01R 13/342; G01R 29/0276; G01R 33/0356; G01R 33/0358; G01R 33/0017; G01R 33/035; G01R 33/0354; H03H 7/01; G11C 11/44; H01L 27/18; H01L 39/223; H01L 39/249; H01L 39/2493; G06N 10/00
See application file for complete search history.

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Fig. 1

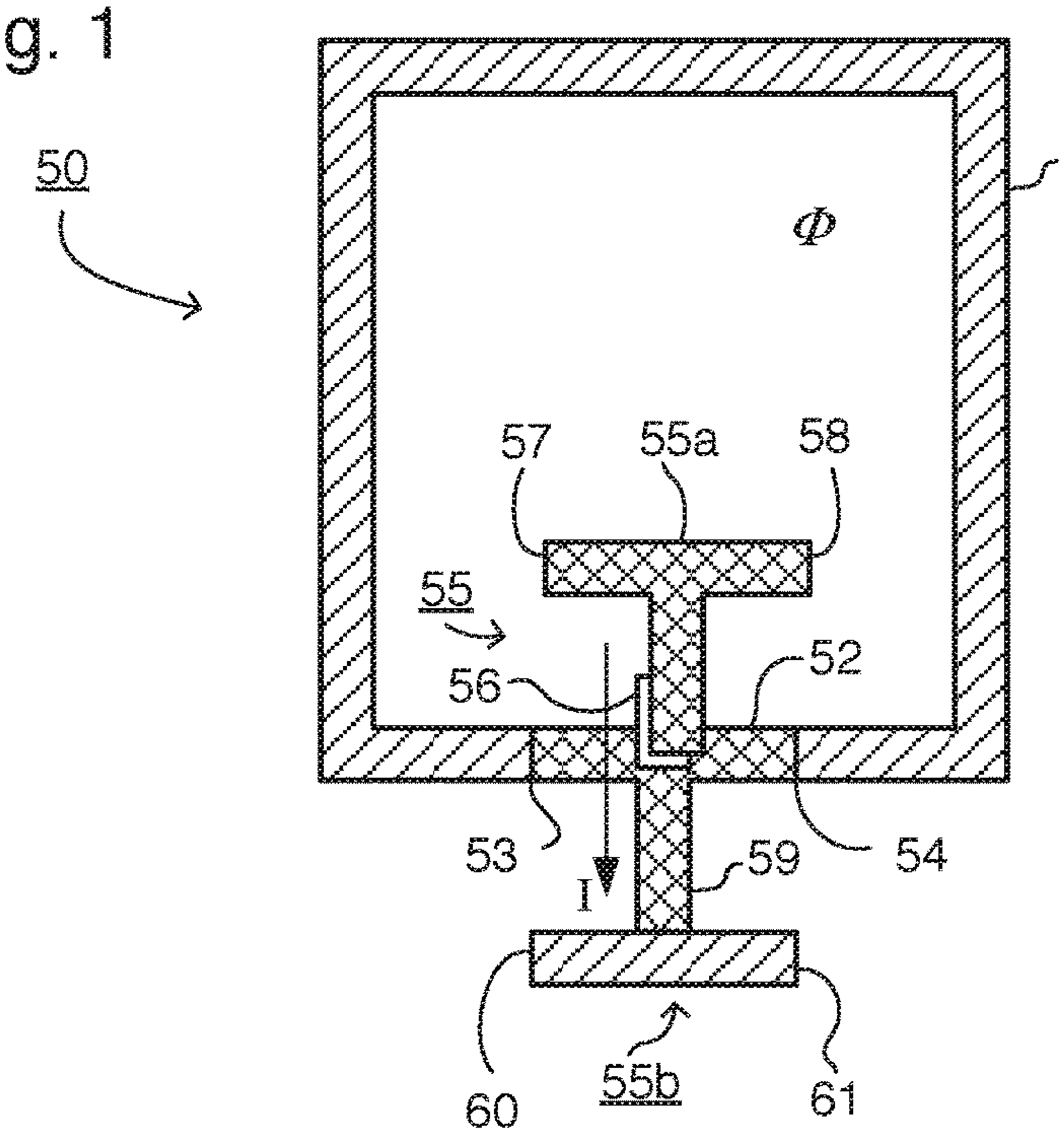


Fig. 2

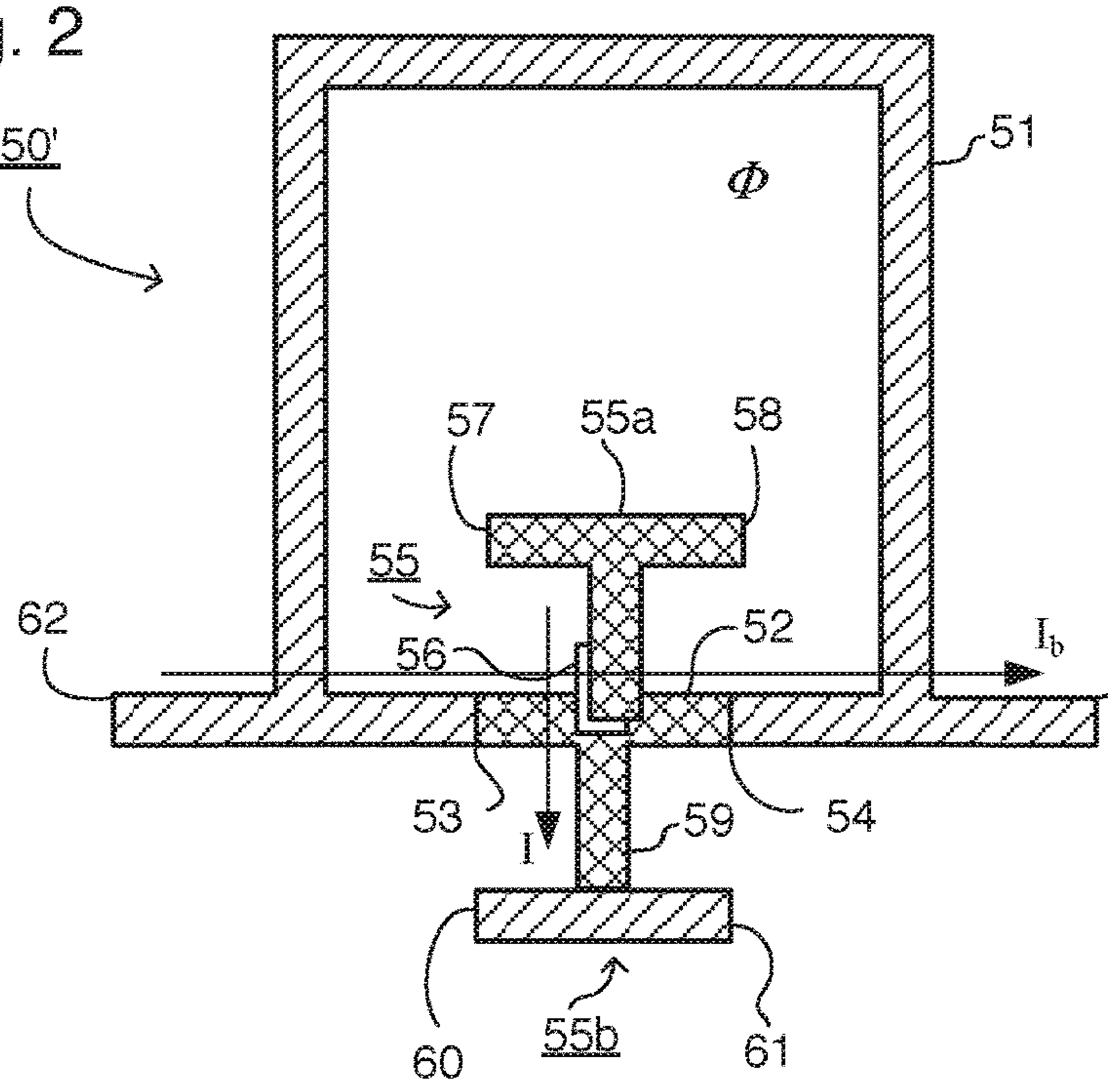


Fig. 3

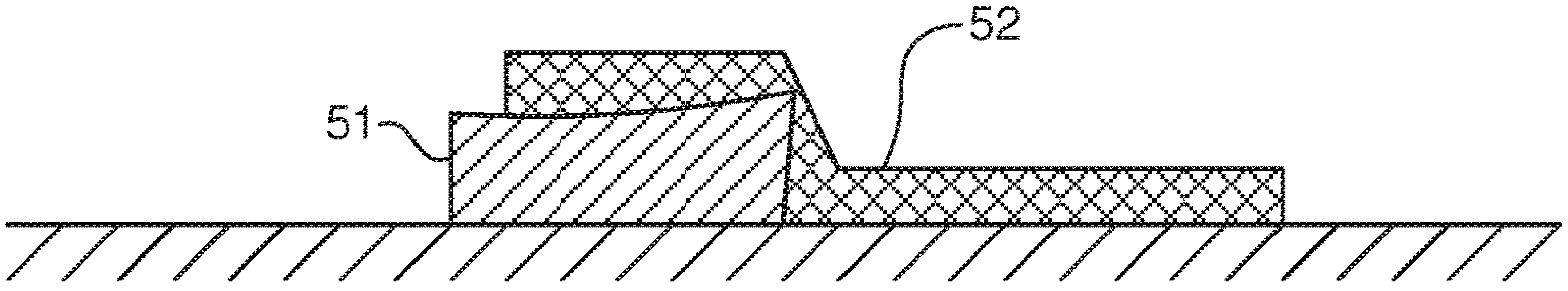


Fig. 4

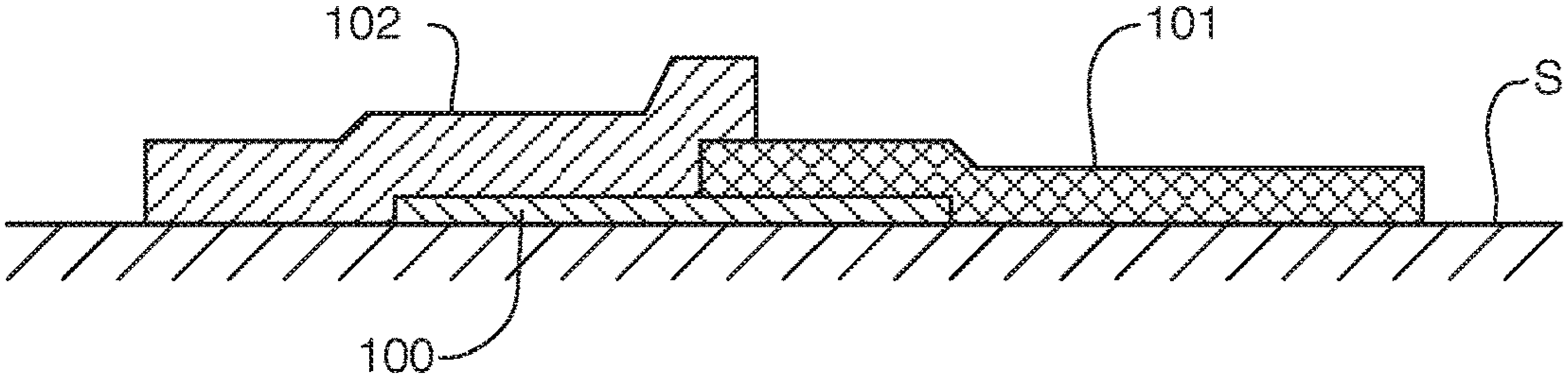


Fig. 5

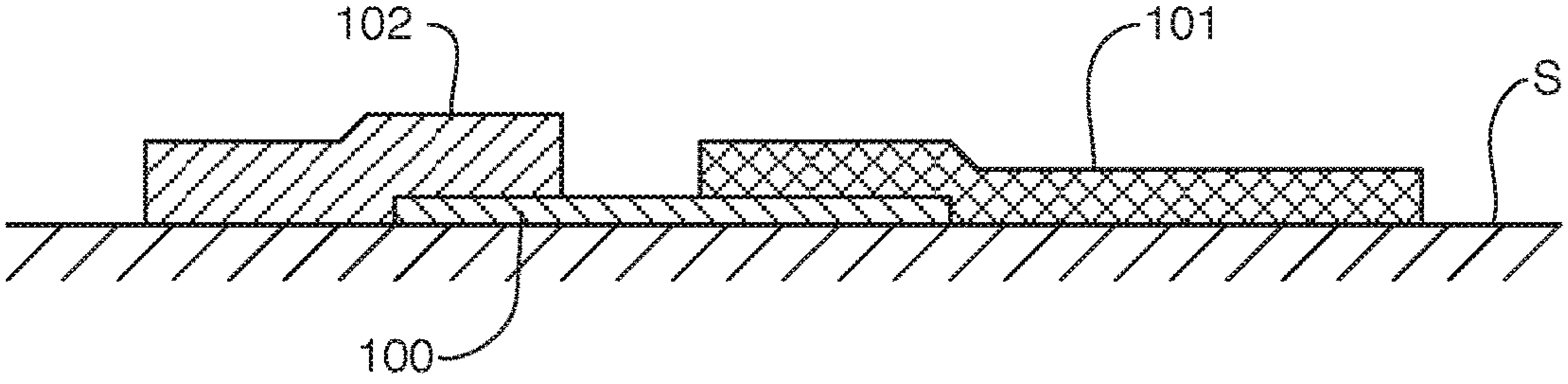


Fig. 6

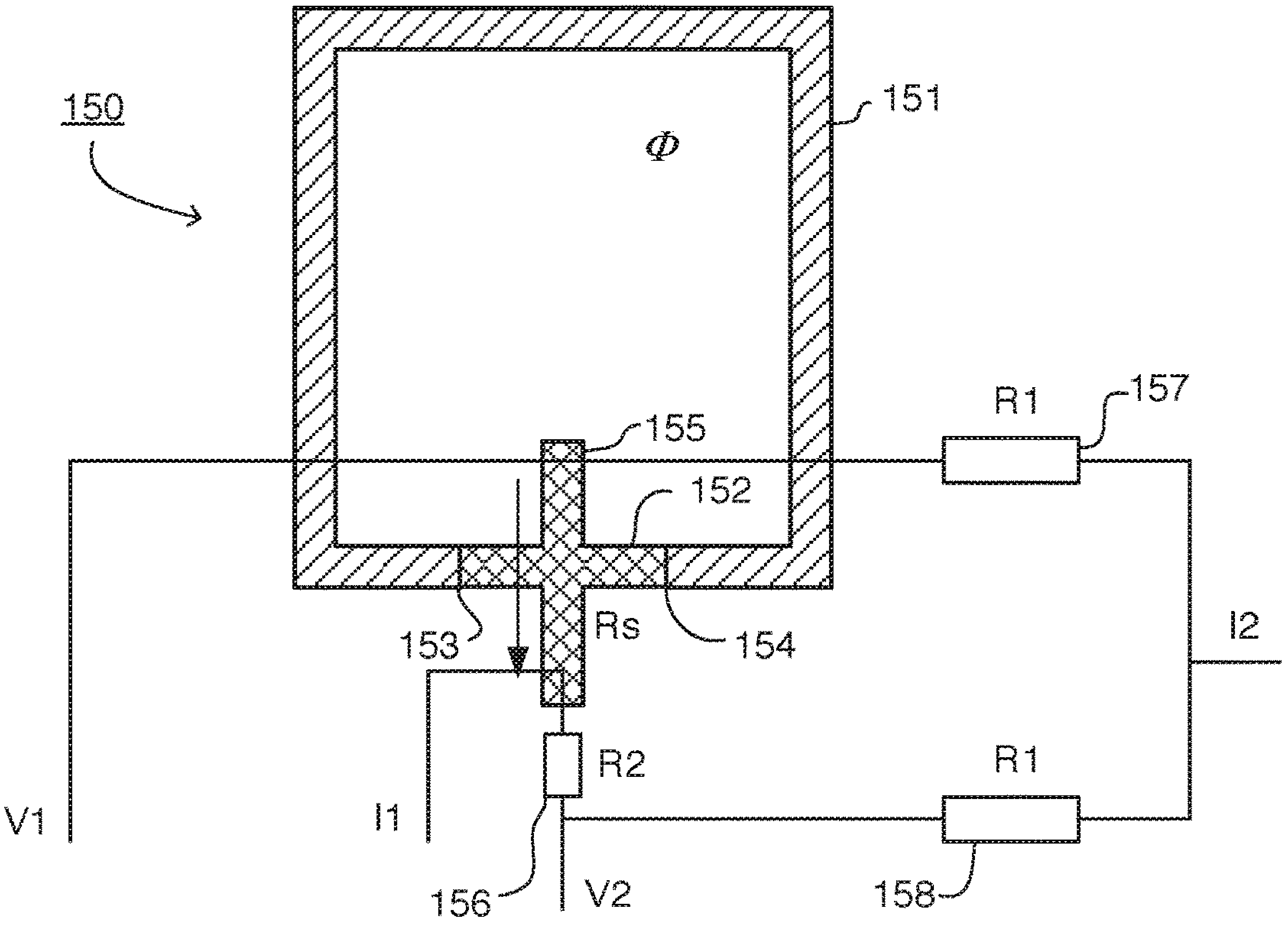
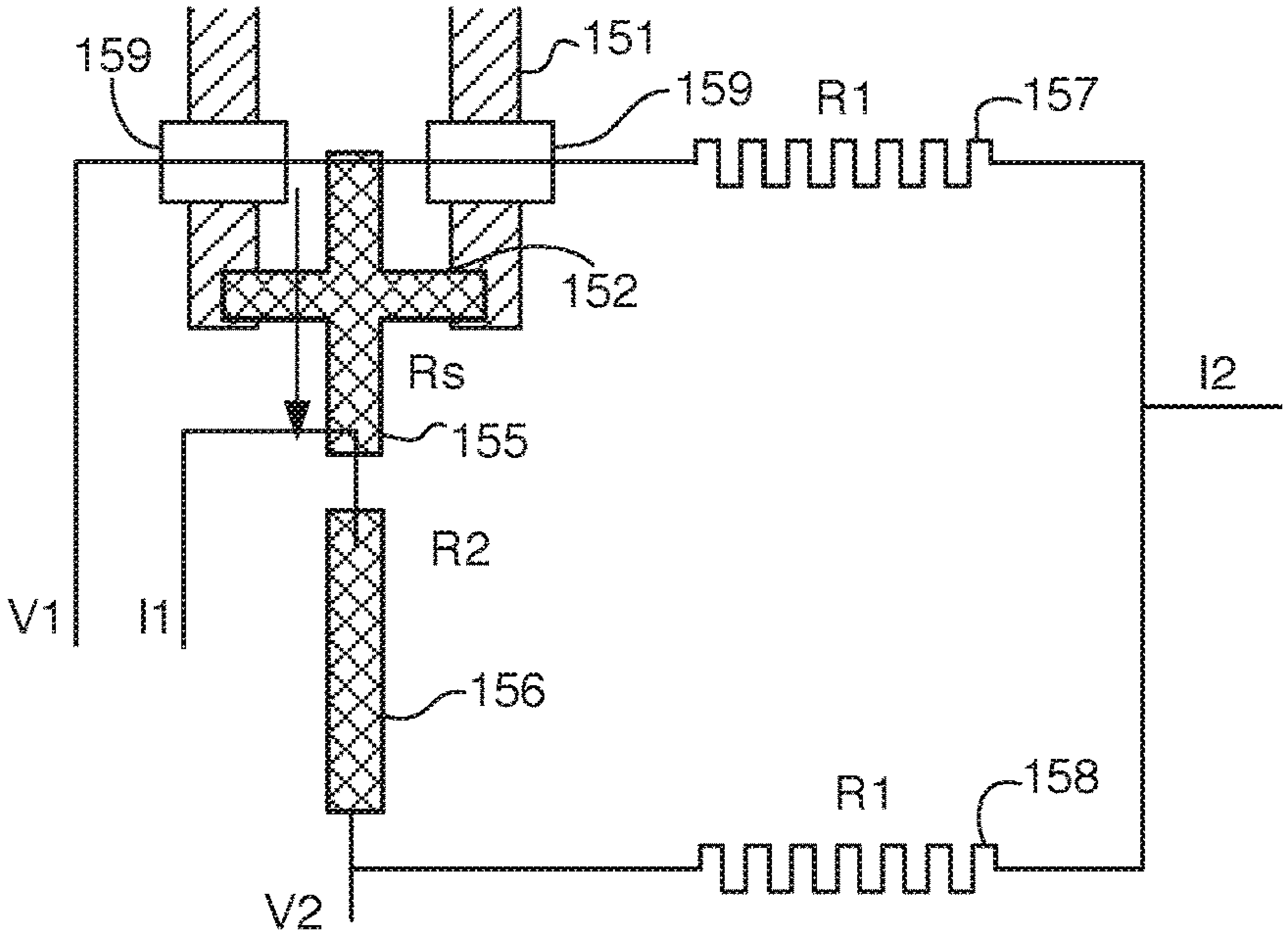


Fig. 7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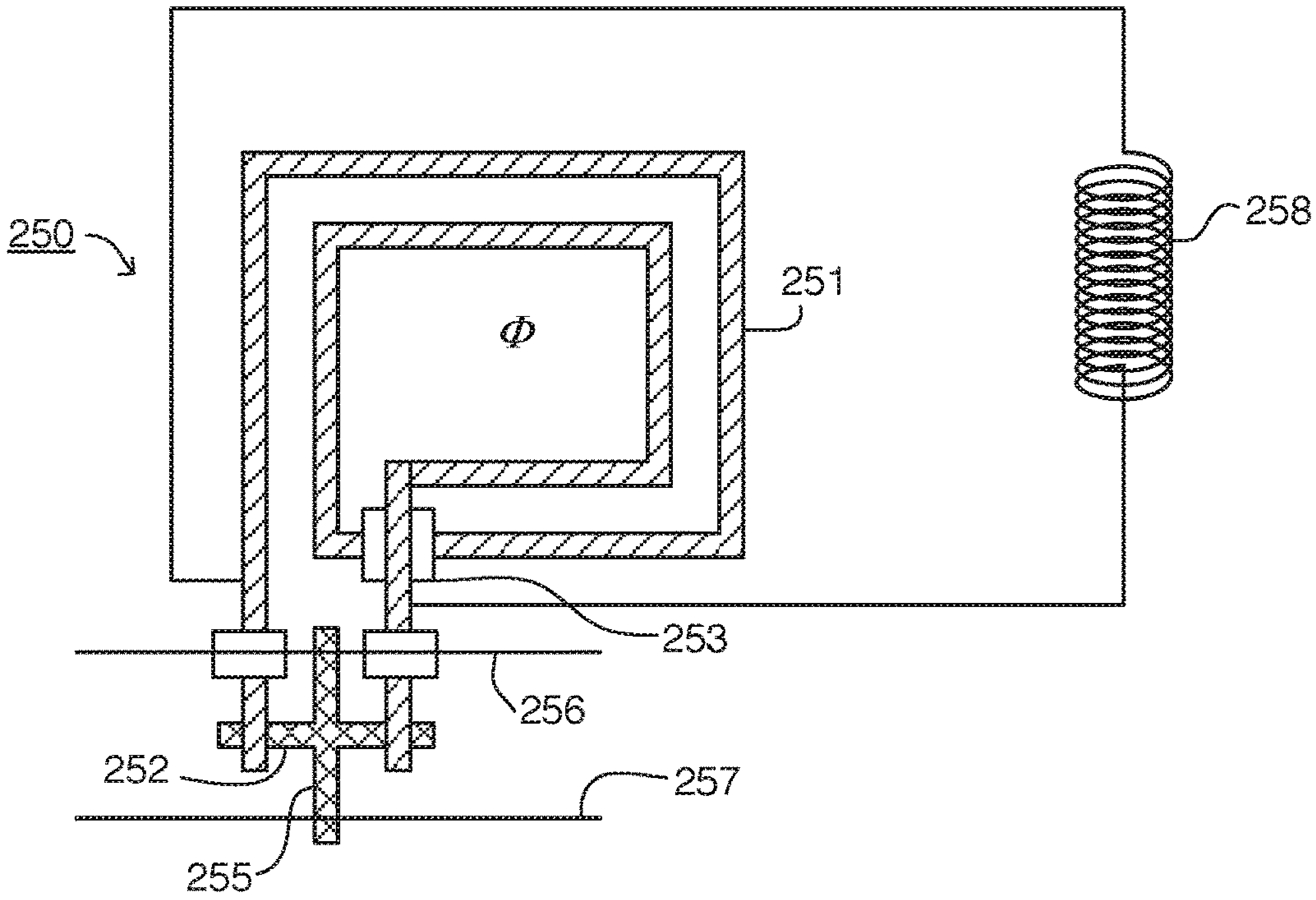
151
159
R1
157
152
Rs
I2
155
R2
V1
I1
156
R1
158
V2

Fig. 8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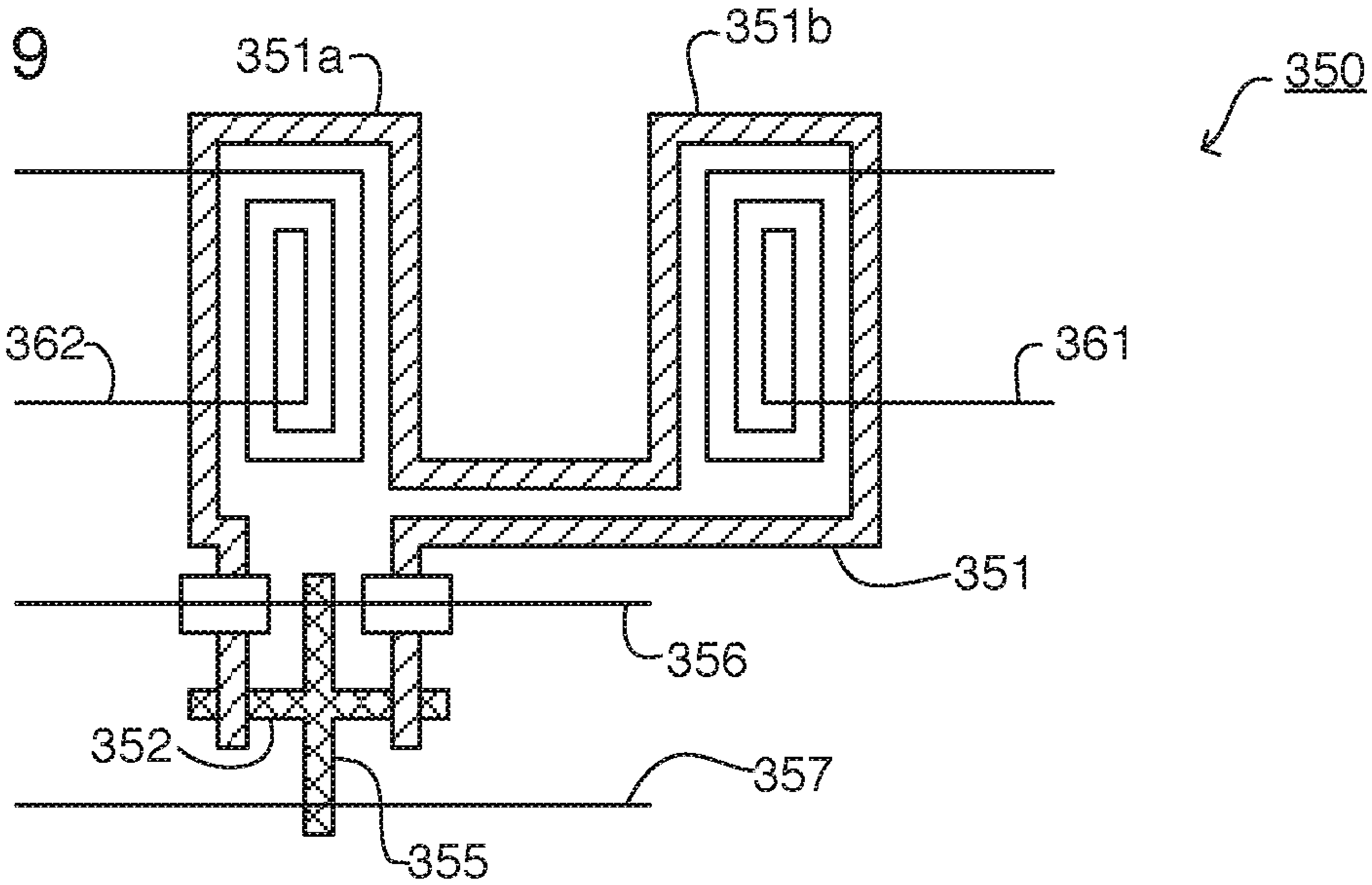
251
Φ
253
256
252
257
255

Fig. 9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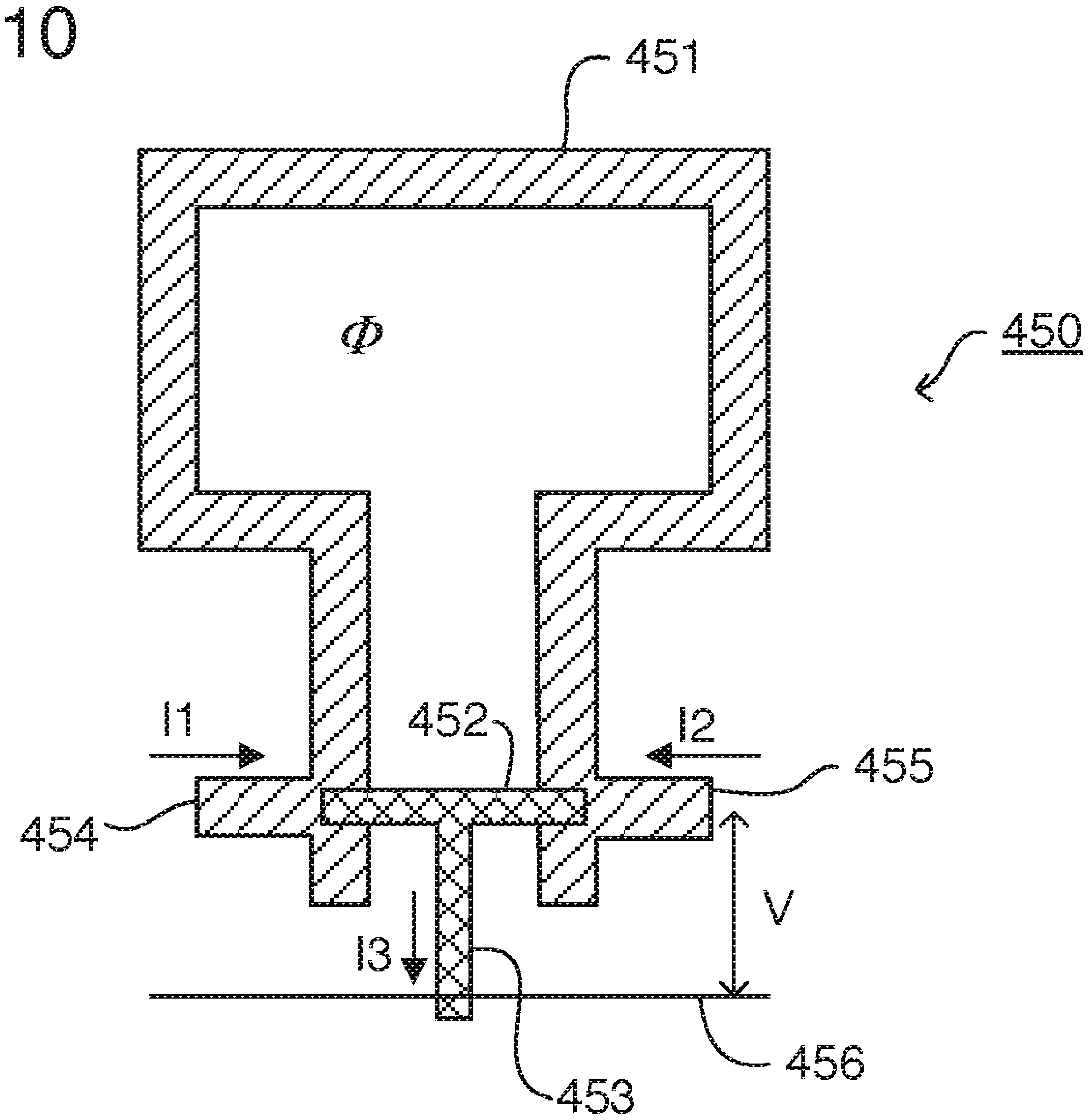
351
356
352
357
355

Fig. 10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Φ
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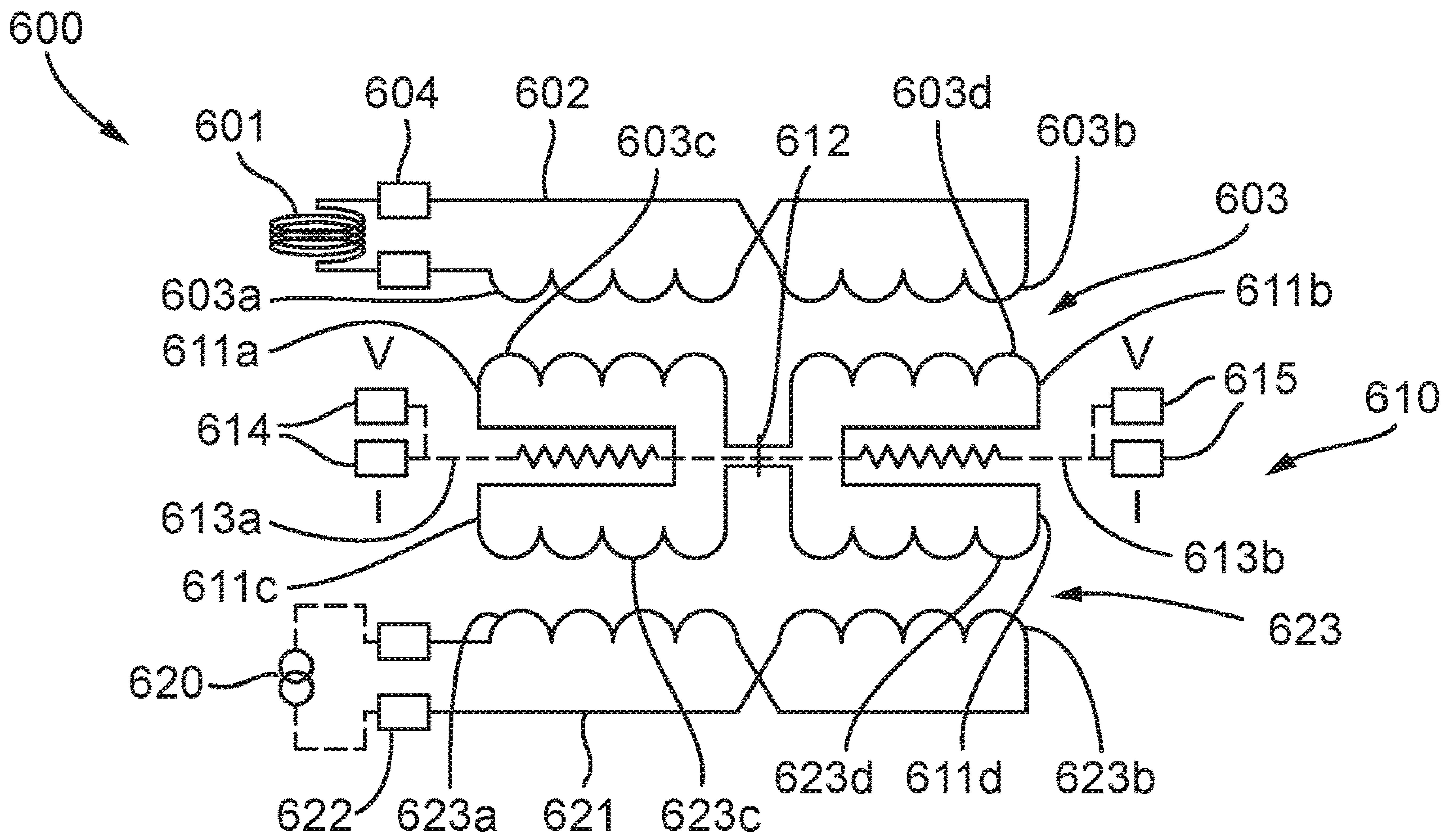
I1
452
I2
455
454
V
I3
456
453

Fig. 11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603c
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603d
603b
603
603a
611a
611b
V
V
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615
610
613a
I
I
613b
611c
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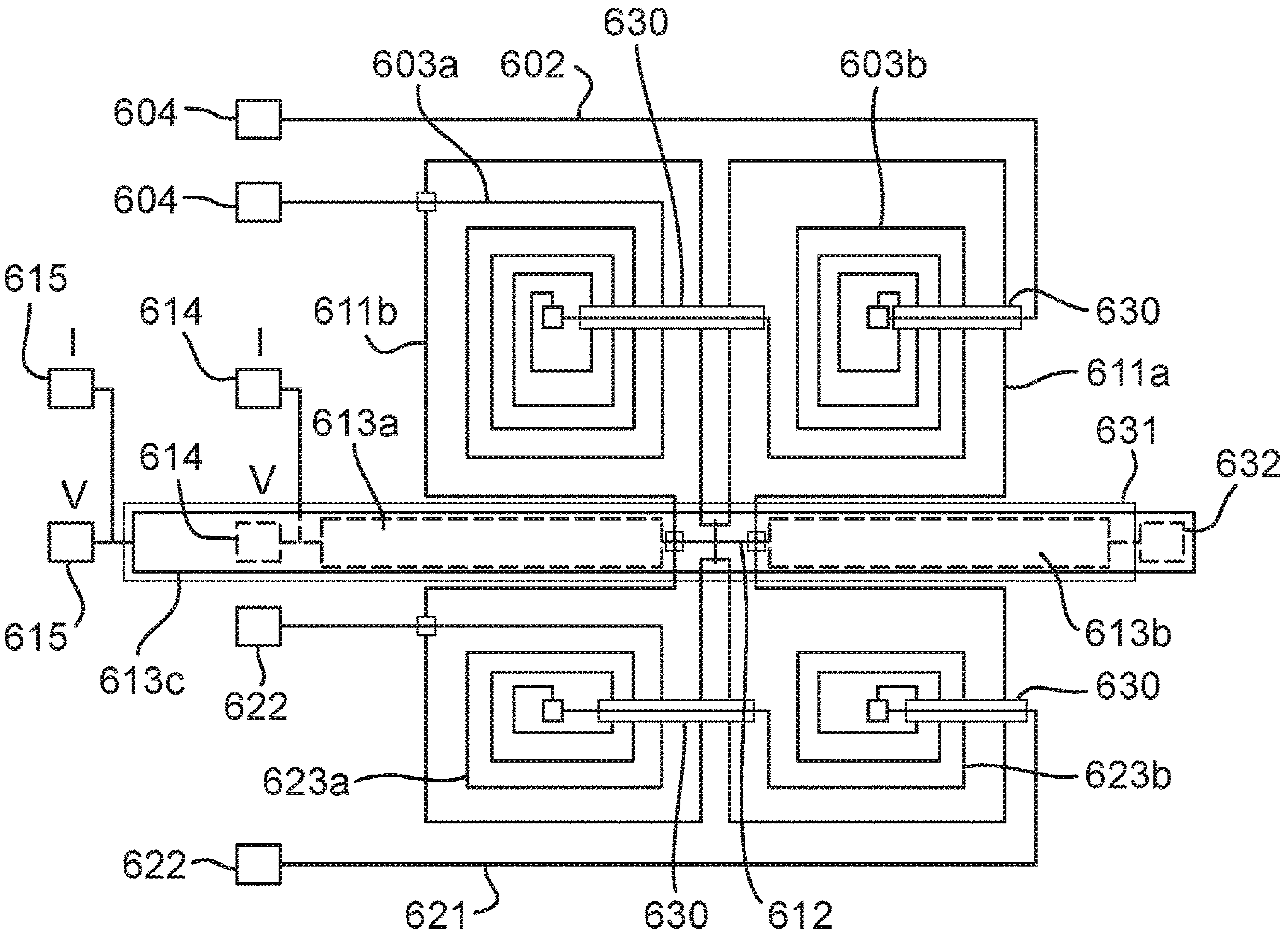
620
622
623a
621
623c
623d
611d
623b

Fig. 12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I
I
611b
611a
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V
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623a
623b
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621
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612

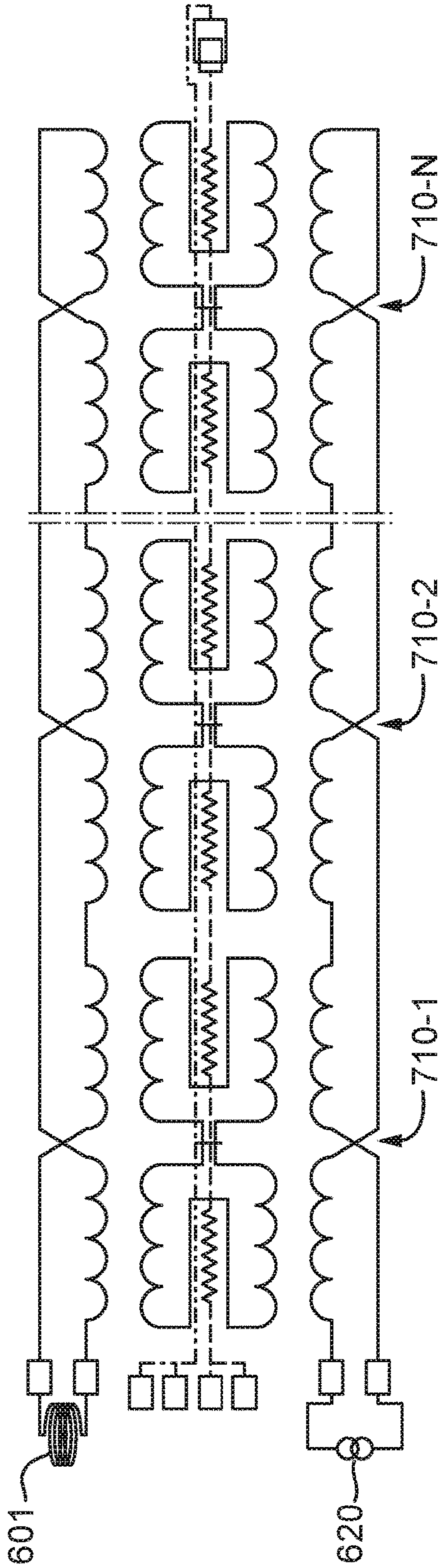

Fig. 13

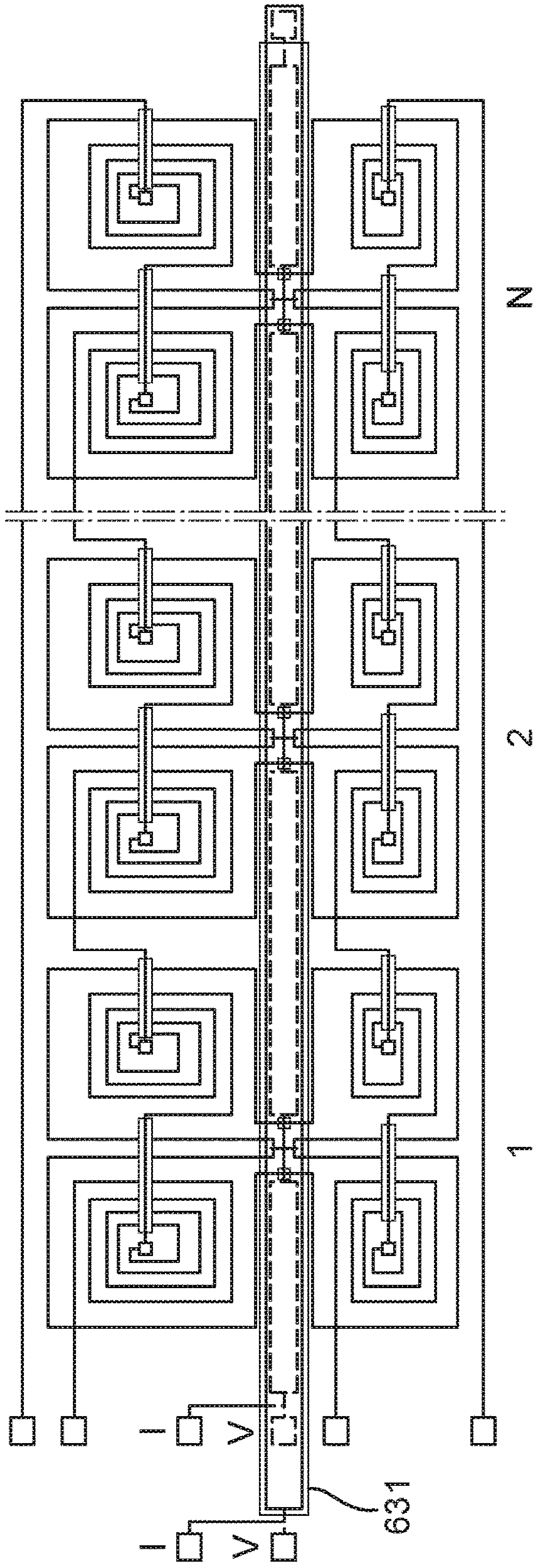

Fig. 14

QUANTUM INTERFERENCE DEVICE, DEVICE INCORPORATING SAME, AND METHOD OF MANUFACTURING A QUANTUM INTERFERENCE DEVICE

The present invention relates to superconducting devices and to methods of manufacturing superconducting devices.

Various quantum interference devices—which can be used as flux sensors, transistors or qubits—are disclosed in WO 2012/007736 A1. Two examples of the devices are depicted in FIGS. **1** and **2** appended hereto.

In the device of FIG. **1**, quantum interference devices **50** comprises a superconducting loop **51** interrupted by a normal conductor segment **52** which connects to the superconducting loop **51** at junctions **53**, **54**. A two branch **10** interferometer **55** is connected to the normal conductor segment **52**. The two branches **55***a*, **55***b* are connected to the midpoint of the normal conductor segment **52** to form a cross.

A first branch **55***a* of the interferometer includes a barrier **56** separating the normal leads **57**, **58** from the normal conductor segment **52**. A second branch **55***b* of the interferometer comprises a normal spur **59** connecting to the normal conductor segment **52** and superconducting leads **60**, **61**. When a current is passed across the interferometer **55**, quasiparticles are reflected from the normal:superconducting interfaces **53**, **54** (Andreev reflection). The flux through the superconducting loop **51** affects the phase difference between interfaces **53** and **54** and hence causes quantum interference between the electrons reflected by the two boundaries. Therefore the current I across the interferometer **55** is sensitive to the flux Φ.

In the variant of FIG. **2**, extra current leads **62**, **63** are provided to convert the interferometer to a transistor. The electrical conductance across the interferometer is controlled by the bias current I_b in the superconducting wire.

WO 2012/007736 A1 teaches that the superconducting parts of such a device be made of aluminium (Al) or niobium (Nb). Al is advantageous as the natural oxidation of Al forms a passivation layer but Nb has a higher critical temperature Tc. The normal conducting parts of the device are suggested to be constructed of Magnesium (Mg), Antimony (Sb), Bismuth (Bi), carbon nanotubes or graphene.

SUMMARY OF THE INVENTION

It is an aim of the invention to provide improved quantum interference devices.

According to the present invention there is provided a quantum interference device comprising a superconducting loop interrupted by a normal conductor segment, and an interferometer connected to the normal conductor segment wherein the superconducting loop comprises a plurality of turns.

According to the present invention there is provided a quantum interference device comprising a superconducting loop interrupted by a normal conductor segment, and an interferometer connected the normal conductor segment; wherein the superconducting loop comprises two or more lobes.

BRIEF DESCRIPTION OF THE DRAWINGS

Exemplary embodiments of the present invention are described further below with reference to the accompanying drawings, in which:

FIG. **1** depicts a quantum interference device known in the art;

FIG. **2** depicts another quantum interference device known in the art;

FIG. **3** depicts a problem occurring in manufacture of a quantum interference device known in the art;

FIG. **4** depicts a junction between a superconductor and a normal conductor in an embodiment of the invention;

FIG. **5** depicts another junction between a superconductor and a normal conductor in an embodiment of the invention;

FIG. **6** schematically depicts a quantum interference device according to an embodiment of the invention;

FIG. **7** is an enlarged view of a part of the quantum interference device of FIG. **6**;

FIG. **8** schematically depicts a quantum interference device according to an embodiment of the invention;

FIG. **9** schematically depicts a quantum interference device according to an embodiment of the invention;

FIG. **10** schematically depicts a quantum interference device according to an embodiment of the invention;

FIG. **11** schematically depicts a gradiometer including quantum interference devices according to an embodiment of the invention;

FIG. **12** depicts an on-chip arrangement of a gradiometer including quantum interference devices according to an embodiment of the invention;

FIG. **13** schematically depicts a gradiometer including multiple quantum interference devices according to an embodiment of the invention; and

FIG. **14** depicts an on-chip arrangement of a gradiometer device including multiple quantum interference devices according to an embodiment of the invention.

In the various drawings, like parts are indicated by like references.

The present inventor has determined that difficulties arise in reliably forming a junction between the normal and superconducting parts of a device such as those depicted in FIGS. **1** and **2**. This can be explained with reference to FIG. **3**, which depicts a junction between the superconducting loop **51** and normal conductor segment **52**. The superconducting loop **51**, e.g. made of niobium, is deposited onto a substrate first and then the normal conductor **52** is deposited to overlap. Candidate materials for the normal conductor segment **52** are aluminium (assuming operation at a temperature higher than 1.2 K) and antimony. Of these, aluminium is on the face of it preferable as it is relatively easy to work with and its self-limiting oxidation behaviour is useful to form a passivation layer. Antimony is a toxic material but has a higher resistivity than aluminium, which is useful as the figures of merit of the quantum interference device improve as the resistance of the normal segment increases. However, the present inventor has determined that it is difficult to form a reliable junction between an aluminium layer **52** and a niobium layer **51** when the aluminium layer is deposited on top of the niobium layer. It is not possible to reverse the order of layers because the native oxide layer, which forms on top of the aluminium layer very quickly on exposure to air, prevents electrical contact.

A junction according to an exemplary embodiment of the invention is depicted in cross-section in FIG. **4**. On substrate S, a bridge layer **100** is provided in the region of the junction. Substrate S can be a standard silicon substrate. The bridge layer is desirably formed of a good conductor—such as gold (Au), silver (Ag) or copper (Cu) or alloys thereof—but does not have to be superconducting. Normal layer **101** is then deposited to overlap part, but not all of, bridge layer **100**. Superconducting layer **102** is deposited to overlap at least part of the bridge layer that is not contacted by the normal layer **101**. An electrical connection between the normal layer **101** and superconducting layer **102** is therefore made through the bridge layer **100**.

Superconducting layer **102** can overlap normal layer **101**. Alternatively superconducting layer **102** can be separated from normal layer **101** so that there is no direct contact between them, as depicted in FIG. **5**. Accordingly, the order of deposition of superconducting layer **102** and normal layer **101** is not constrained.

The bridge layer also increases the freedom of choice for materials for the superconducting layer **102** and normal layer **101**. It is not necessary to consider the properties of an interface between the normal layer **101** and superconducting layer **102** since the electrical connection is made via the bridge layer **100**. Instead, the compatibility of the bridge layer **100** with each of the normal layer **101** and superconducting layer **102** determines the properties of the junction.

Gold has been found by the present inventor to make good electrical connection to various superconducting materials, including niobium (T_c=9.26 K), lead (T_c=7.19 K) and aluminium (T_c=1.20 K). Likewise, gold has been found to make good electrical connection to materials suitable for use as the normal layer such as aluminium (at higher temperatures than 1.2 K), titanium (Ti), and alloys thereof. Since reliable connections can be formed, the present invention allows for a reduction in costs of manufacturing quantum interference devices. The improvement in yield more than makes up for the additional cost of the additional steps involved in forming the bridge layer.

Standard processing steps known for semiconductor manufacturing can be used to manufacture a quantum interference device according to an embodiment of the invention. E-beam lithography and photo-lithography can be used for patterning; the invention does not require especially high resolution patterning. Layers can be deposited by techniques such as sputtering and various vapour deposition techniques.

The present invention can be applied to a variety of different types of quantum interference devices, including SQUIDs, HyQUIDs, and Andreev interferometers. Quantum interference devices according to the invention can be used for various purposes, e.g. as magnetic field (or flux) sensors, transistors, qubits, or readout devices for qubits.

In an embodiment of the invention, at least some normal parts of the quantum interference device are made of titanium. Titanium has heretofore not been considered a suitable material for such uses as it is chemically active and oxidises in air, without forming a sealing layer preventing further oxidation in the way that aluminium does. Therefore, it would be expected that a titanium layer would completely oxidise in time, rendering any device relying on its conductivity non-functional.

However, a titanium oxide layer formed through oxidation of titanium in air does not in practice grow indefinitely. Rather the rate of growth slows and over a period of several years, likely about 4, the thickness of the titanium oxide layer stabilises at about 40 nm, having consumed a little less than that of the thickness of the original titanium layer. Therefore, by providing an initial titanium layer of thickness greater than the passivation depth of titanium, e.g. greater than 40 nm, it can be ensured that a conductive layer of non-oxidised titanium remains. In an embodiment the initial titanium layer has a thickness at least 20 nm greater than the passivation depth of titanium.

In a quantum interference device according to an embodiment of the invention, use of a titanium layer as a normal part interrupting a superconducting loop can provide an additional advantage. As the titanium layer oxidises, its resistance increases, increasing resistance of normal parts of the device. This improves operation of the device.

An improved quantum interference device **150**, e.g. useable as a flux sensor or magnetometer, is schematically depicted in FIG. **6**. Quantum interference device **150** comprises a superconducting loop **151** interrupted by a normal conductor segment **152**. The superconducting loop **151** and normal conductor segment **152** can be made of any of the respective superconducting and normal conducting materials discussed above. Normal: superconducting junctions **153**, **154** are formed at the ends of the normal conductor segment **152**. A crosspiece **155** is connected at the midpoint of normal conductor segment **152** so as to form an interferometer. Crosspiece **155** is desirably formed of the same material and at the same time as normal conductor segment **152**. As discussed above, when a flux Φ is applied to the superconducting loop **151**, quantum interference will occur between electrons reflected at the junctions **153**, **154** so that the effective resistance of the crosspiece **155** is cyclically dependent on the flux Φ passing through superconductor loop **151**.

A conventional approach to using a quantum interference device **150** to measure flux is to apply a known current through the crosspiece **155** and measure the resulting voltage across the crosspiece. As the flux Φ through the superconducting loop **151** changes, it causes a cyclic change in the resistance of the crosspiece, leading to a cyclic change in the voltage across the crosspiece at a fixed current through it. Since the resistance variation may be only a few percent of the total resistance of the crosspiece the cyclic voltage change that is superimposed on a non-oscillating voltage the relative amplitude of the quantum oscillations may be small as well. Therefore, the current fluctuations caused by changes in flux are difficult to measure, particularly in the case of small flux changes.

In the quantum interference device **150**, the crosspiece **155** is placed in a Wheatstone bridge arrangement to enable direct measurement of the voltage change independently of the value of the non-oscillating voltage component. The Wheatstone bridge arrangement can be formed directly on the same substrate (i.e. on-chip) as the quantum interference device **150** so that the possibility of noise being picked up by long connecting leads can be avoided. Also, because the Wheatstone bridge is on-chip, it will be at a low temperature and so thermal noise is reduced substantially. A preamplifier can also be provided on the substrate adjacent the quantum interference device **150** to provide further noise immunity.

As depicted in FIG. **6**, a resistor **156** is placed in series with the crosspiece **155**. Resistor **156** has a resistance R2 that is equal to the nominal resistance Rs of the crosspiece **155**. A series circuit of resistors **157**, **158** is connected in parallel with the series circuit of crosspiece **155** and resistor **156**. Resistors **157**, **158** both have resistance R1. To measure, terminal V1 is connected to one end of crosspiece **155** and resistor **157**. Terminal V2 is connected to the opposite end of resistor **156** and resistor **158**. A sensor output is obtained by measuring the potential difference across terminals V1, V2 at a fixed bias current between terminal I1, connected to the junction between crosspiece **155** and resistor **156**, and terminal I2, connected to the junction between resistors **157** and **158**. To make relative changes in the current between I1 and I2 during measurements negligible the resistance R1 is made much greater than Rs.

FIG. **7** depicts in greater detail how the circuit of FIG. **6** is effected on a substrate. Quantum interference device **150** can be formed by depositing the superconducting loop **151** and then overlaying the normal parts. Resistor **156** is desirably formed of the same material as the normal parts of the quantum interference device **150**. It is desirably formed of the same material and has the same geometry as crosspiece **155** so as to have the same nominal resistance.

Insulating pads **159** are placed over the superconducting loop **151**. Conductive traces can then be applied to join the inner end of crosspiece **155** to terminal V1 and to resistor **157**. Resistor **157** and resistor **158** can be formed in the same step as the conductive traces by forming them as long meandering parts. The conductive traces forming resistors **152**, **158** can have much more complex paths than those depicted in the Figure. Desirably, resistors **157** and **158** have the same dimensions and geometry and are formed in the same step to ensure that they have the same resistance. That their resistances are equal is more important than the exact value of their resistances.

Advantageously, resistors **156**, **157** and **158** are formed from the same material and in close proximity to crosspiece **155**. Therefore, any environmental variations, e.g. temperature changes, will affect the resistors equally as crosspiece **155** so that the relationships between their resistances remain constant. The Wheatstone bridge arrangement is possible with a hybrid quantum interference device because it is the resistance of the normal crosspiece that is being measured. With a conventional SQUID, the Wheatstone bridge arrangement would require a normal resistance having an equal resistance to the superconducting loop, which is impractical.

It is to be noted that the HyQUID of FIGS. **6** and **7**, when used as a magnetometer, does not require the tunnelling barrier as used in the prior art. The HyQUID of FIGS. **6** and **7** can be fabricated using fewer steps than a magnetometer based on a SQUID.

Another improved quantum interference device **250** is schematically depicted in FIG. **8**. Quantum interference device **250** is, for example, useable as a flux sensor or a magnetometer. Quantum interference device **250** includes a superconducting loop **251** interrupted by a normal conductor segment **252**. A crosspiece **255** is connected to the middle of the normal conductor segment **252** in order to form an interferometer. Read-out leads **256**, **257** are connected to the end of the crosspiece **255**.

As shown in FIG. **8**, superconducting loop **251** is provided in the form of a coil with multiple nested loops. In the Figure, only two loops are shown, but an embodiment can have as many loops as is required and/or can be accommodated in the available space. The loops can be concentric but need not be. The loops all surround a common area. Due to the increased flux linkage, the amplitude of the resistance oscillations induced by changing flux is approximately proportional to the number of loops of the superconducting loop **251**, after correcting for differences in the area of each loop. An insulating pad **253** is provided to enable the superconducting loop **251** to cross over itself without electrical contact. By applying an insulating layer, it is also possible to stack superconducting loops vertically. A pickup coil **258**, desirably also superconducting, can be connected to the superconducting loop **251** in order to enable measurement of magnetic fields at a remote location.

FIG. **9** schematically depicts another improved quantum interference device **350**. Quantum interference device **350** comprises a superconducting loop **351** interrupted by a normal conductor segment **352**. A crosspiece **355** is attached the midpoint of normal conductor segment **352** in order to form an interferometer. Read-out leads **356**, **357** are connected to the ends of crosspiece **355**. Superconducting loop **351** has two lobes **351***a*, **351***b*. The two lobes are adjacent to each other rather than overlapping or touching. They do not have to be directly adjacent nor close. The two lobes can be formed conveniently in the same layer of an integrated circuit. A pickup coil **362** can be provided in first lobe **351***a*. Pickup coil **362** allows for measuring the magnetic field at a remote location. A feedback coil **361** can be provided in second lobe **351***b*. Feedback coil **361** allows cancellation of magnetic fields, e.g. stray magnetic fields, and also to flux modulate the signal. Pickup coil **362** and feedback coil **361** are superconducting.

FIG. **10** depicts another improved quantum interference device **450**. Both currents I1 and I2 flow in the direction **452** and converge at T-junction so I3=I1+I2). Quantum interference device **450** comprises a superconducting loop **451** interrupted by a normal conductor segment **452**. Superconducting loop **451** is provided with terminals **454**, **455** to which a bias current is applied in use. A normal conducting spur **453** is connected to the midpoint of normal conductor segment **452**. By applying a potential difference V between a read-out lead **456** connected to the end of spur **453** and superconducting terminal **455**, a current I3 flows through normal conductor spur **453**. Because of quantum interference in the normal conductor segment **452**, current I3 includes a cyclic component dependent on changes in flux Φ passing through superconducting loop **451**.

The normal conductor segment **452** and normal conductor spur **453** form a T-shaped interferometer. This arrangement can be formed in fewer steps than a cross-shaped interferometer which requires connections to a branch of the interferometer within the superconducting loop.

FIG. **11** depicts a gradiometer **600** using a four-lobed HyQUID **610** according to an embodiment of the invention. In FIG. **11**, superconducting conductors are indicated by solid lines and normal conductors are depicted by dashed lines. The gradiometer also comprises a pick-up circuit and a feedback circuit which couple to the HyQUID by respective flux transformers.

The pick-up circuit comprises a pick-up coil **601** is connected via superconducting pick-up leads **602** to the pick-up side of a superconducting flux transformer **603**. The pick up side of flux transformer **603** has two superconducting coil sections **603***a*, **603***b* which are connected so that the current induced by pick-up coil **601** flows in opposite senses in coil sections **603***a*, **603***b*. Connections between the pick-up coil **601** and superconducting pick-up leads **602** can be made via on-chip contact pads **604**. The pick-up coil **601** and any connecting leads are superconducting.

The feedback circuit mirrors the pick-up circuit and allows a controlled flux to be applied to the HyQUID **610** so as to modulate the measurement signal or adjust the measurement range. A feedback current source **620** is connected to superconducting feedback leads **621** via on-chip contact pads **622**. Feedback leads **621** are connected to feedback flux transformer **623**. Specifically, feedback leads **621** are connected to coil sections **623***a*, **623***b* of feedback flux transformer **623** so that current flows in opposite senses in coil sections **623***a*, **623***b*.

HyQUID **610** comprises four superconducting lobes **611***a-d* connected symmetrically around an interferometer **612**. Lobes **611***a-d* are adjacent rather than overlapping or touching but do not need to be close together. The arrangement of lobes is like a four-leafed clover with the interferometer at the centre. The lobes may be rectangular or rounded. The four-lobed HyQUID can be regarded as two two-lobed HyQUIDs sharing a normal segment.

Two of the lobes **611***a*, **611***b* include respective superconducting sections **603***c*, **603***b* which couple to a respective one of coil sections **603***a*, **603***b* of the pick-up flux transformer **603**. Another two of the lobes **611***c*, **611***d* couple with coil sections **623***a* and **623***b* respectively of feedback flux transformer **623**. To cancel the stray magnetic fields the total magnetic flux through the left-hand part of the gradiometer, **611***a*, **611***c*, must be equal to the total magnetic flux through the right-hand-hand part of the gradiometer, **611***b*, **611***d* (FIG. **11**).

Interferometer **612** is formed of a normal conductor and has the shape of a cross. Normal read-out leads **613***a,b* terminating in contact pads **614**, **615** allow a current I to be applied across the cross-piece of the interferometer **612**. Potential difference V is measured to provide the output signal. Desirably, read-out leads **613** have a low resistance. FIG. **12** shows in more detail how the gradiometer of FIG. **11** can be laid out on an integrated circuit using a minimum number of layers. Insulating pads **630** are provided to allow pick-up leads **602** and feedback leads **621** to cross the lobes of HyQUID **610** so as to connect with the respective coil sections of the flux transformers **603**, **623**. To maximise inductive coupling, the flux transformers are formed by spiral coils connected to the pick-up leads and feedback leads respectively and located within the lobes of the HyQUID **610**.

Read-out leads **613***a,b* are formed as broad tracks in order to minimise their resistance. One readout lead **613***b* is folded back over the top of the other read-out lead **613***b*, with an elongate insulating pad **631** in between. This arrangement makes the area enclosed within current leads negligible. This minimises inductive coupling of readout wires to the flux-sensitive loops and pick-up of interference.

FIGS. **13** and **14** are respectively schematic and chip layouts for a multi-stage gradiometer **700**. Each gradiometer stage **710-1** to **710**-N is equivalent of the gradiometer **600** of FIGS. **11** and **12**. The pick-up coil **601** is connected each of the pick-up side flux transformers in series. Similarly the feedback current source **620** is connected in series to each of the feedback side flux transformers. The interferometers of the gradiometer stages are connected in series so that their resistances add, hence summing the signal measured from the pick-up coil. The total inductive coupling between spiral coils and interferometer loops increases proportionally to the number of gradiometer stages. The thermal magnetic flux noise is inversely proportional to the square root of the number of stages and decreases with that number. Again, one readout lead is folded back over the other to minimise the enclosed area and hence minimise the inductive coupling of the readout wires to the flux-sensitive loops and induced noise due to interference.

Embodiments of the invention include:

A) A superconducting device comprising: a substrate; a bridge layer formed above the substrate; a superconducting layer formed above the bridge layer and in direct electrical contact with a part of the bridge layer; and a normal conducting layer formed above the bridge layer and in direct electrical contact with a part of the bridge layer. This embodiment can provide an improved approach to forming junctions between superconductors and normal conductors.

B) A superconducting device according to embodiment A wherein the bridge layer is formed from a metal selected from the group consisting of: gold, silver, copper and alloys thereof.

C) A superconducting device according to embodiment A or B wherein the superconducting layer is formed from a metal selected from the group consisting of: niobium, lead, aluminium and alloys thereof.

D) A superconducting device according to embodiment A, B or C wherein the normal conducting layer is formed from a metal selected from the group consisting of: titanium, aluminium and alloys thereof.

E) A superconducting device according to embodiment D wherein the normal conducting layer is formed from a layer of titanium having a thickness greater than the passivation depth of titanium when manufactured, desirably greater than 20 nm plus the passivation depth of titanium, for example 40 nm.

F) A superconducting device according to embodiment D wherein the normal conducting layer is formed from a layer of titanium having a layer of titanium oxide thereon, the layer of titanium oxide having a thickness less than or equal to 40 nm.

G) A quantum interference device comprising a superconducting device according to any one of the preceding embodiments wherein the superconducting layer forms a loop and the normal conducting layer interrupts the loop; and further comprising an interferometer connected to the normal conducting layer.

H) A method of manufacturing a superconducting device comprising the steps of: forming a bridge layer above the substrate; forming a superconducting layer above the bridge layer and in direct electrical contact with a part of the bridge layer; and forming a normal conductor layer above the bridge layer and in direct electrical contact with a part of the bridge layer.

I) A method according to embodiment H wherein the superconducting layer is formed before the normal conducting layer.

J) A method according to embodiment H wherein the superconducting layer is formed after the normal conducting layer.

K) A method according to embodiment H, I or J wherein the bridge layer is formed from a metal selected from the group consisting of: gold, silver, copper and alloys thereof.

L) A method according to embodiment H, I, J or K wherein the superconducting layer is formed from a metal selected from the group consisting of: niobium, lead, aluminium and alloys thereof.

M) A method according to any one of embodiments H to L wherein the normal conducting layer is formed from a metal selected from the group consisting of: titanium, aluminium and alloys thereof.

N) A method according to any one of embodiments H to M wherein the normal conducting layer is formed from a layer of titanium having a thickness greater than 40 nm when manufactured.

O) A method according to embodiment N further comprising allowing the layer of titanium to oxidise.

P) A quantum interference device comprising a superconducting loop interrupted by a normal conductor segment wherein the normal conductor segment is formed from a layer of titanium having a thickness greater than the passivation depth of titanium when manufactured, desirably greater than 20 nm plus the passivation depth of titanium, for example 40 nm.

Q) A quantum interference device according to embodiment P further comprising an interferometer connected to the normal conductor segment and formed from a layer of titanium having a thickness greater than the passivation depth of titanium when manufactured, desirably greater than 20 nm plus the passivation depth of titanium, for example 40 nm.

R) A quantum interference device comprising a superconducting loop interrupted by a normal conductor segment, and an interferometer connected to the normal conductor segment; wherein the interferometer comprises one arm of a Wheatstone bridge.

S) A quantum interference device according to embodiment R wherein the Wheatstone bridge is formed on the same substrate as the quantum interference device.

T) A quantum interference device according to embodiment S wherein the Wheatstone bridge comprises a first resistor formed in series with the interferometer and having the same nominal resistance as the interferometer and second and third resistors forming a series circuit in parallel with the series circuit comprising the first resistor and the interferometer.

U) A quantum interference device according to embodiment T wherein the second and third resistors have the same nominal resistance, the nominal resistance of the second and third resistors being greater than the nominal resistance of the interferometer and the first resistor.

V) A quantum interference device according to embodiment U or T wherein the second and third resistors are each formed by a meandering conductive trace.

W) A quantum interference device comprising a superconducting loop interrupted by a normal conductor segment, a normal spur connected to the normal conductor segment and current terminals connected to the superconducting loop opposite the ends of the normal conductor segment.

Having described exemplary embodiments of the present invention it will be appreciated that variations on the described embodiments can be made. For example, although the bridge layer is shown as formed directly on a substrate it can be formed on other layers, e.g. an insulator. Features of the different devices described above can be combined in all feasible combinations. The present invention is not to be limited by the above description but rather by the appended claims.

The present invention claims priority from British Patent application GB1515620.1 filed 3 Sep. 2015, which document is hereby incorporated by reference.

The invention claimed is:

1. A quantum interference device comprising a superconducting loop interrupted by a normal conductor segment, and an interferometer connected to the normal conductor segment wherein the superconducting loop comprises a plurality of turns, wherein the plurality of turns comprises a plurality of nested loops.

2. A quantum interference device according to claim **1** wherein the plurality of turns comprises a plurality of adjacent lobes.

3. A quantum interference device according to claim **2** further comprising a coil located within a lobe of the superconducting loop.

4. A quantum interference device according to claim **3** having two lobes and a coil located within each lobe of the superconducting loop.

5. A device according to claim **1** further comprising a bridge layer at a junction between a superconductor and a normal conductor.

6. A device according to claim **5** wherein the bridge layer is formed from a metal selected from the group consisting of: gold, silver copper and alloys thereof.

7. A device according to claim **1** wherein the superconducting loop is formed from a metal selected from the group consisting of: niobium, lead, aluminium and alloys thereof.

8. A device according to claim **1** wherein the normal conductor segment is formed from a metal selected from the group consisting of: titanium, aluminium and alloys thereof.

9. A device according to claim **8** wherein the normal conductor segment is formed from a layer of titanium having a thickness greater than 40 nm.

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